LCA Case Studies

Influence of Functional Unit on the Life Cycle Assessment of Traction Batteries

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Abstract

Goal, Scope and Background. This paper describes the influence of the choice of the functional unit on the results of an environmental assessment of different battery technologies for electric and hybrid vehicles. Battery, hybrid and fuel cell electric vehicles are considered as being environmentally friendly. However, the batteries they use are sometimes said to be environmentally unfriendly. At the current state of technology different battery types can be envisaged: lead-acid, nickel-cadmium, nickel-metal hydride, lithium-ion and sodium-nickel chloride. The environmental impacts described in this paper are based on a life cycle assessment (LCA) approach.
One of the first critical stages of LCA is the definition of an appropriate and specific functional unit for electric and hybrid vehicle application. Most of the known LCA studies concerning batteries were performed while choosing different functional units, although this choice can influence the final results. An adequate functional unit, allowing to compare battery technologies in their real life vehicle application should be chosen.
The results of the LCA are important as they will be used as a decision support for the end-of-life vehicles directive 2000/53/EC (Official Journal of the European Communities L269/24 2000). As a consequence, a thorough analysis is required to define an appropriate functional unit for the assessment of batteries for electric vehicles. This paper discusses this issue and will mainly focus on traction batteries for electric vehicles.

Main Features. An overview of the different parameters to be considered in the definition of a functional unit to compare battery technologies for battery electric vehicle application is described and discussed. An LCA study is performed for the most relevant potential functional units. SimaPro 6 is used as a software tool and Eco-indicator 99 as an impact assessment method. The influence of the different selected functional units on the results (Eco-indicator Points) is discussed. The environmental impact of the different electric vehicle battery technologies is described. A sensitivity analysis illustrates the robustness of the obtained results.

Results and Discussion. Five main parameters are considered in each investigated functional unit: an equal depth of discharge is assumed, a relative number of batteries required during the life of the vehicle is calculated, the energy losses in the battery and the additional vehicle consumption due to the battery mass is included and the same lifetime distance target is taken into account. On the basis of the energy content, battery mass, number of cycles and vehicle autonomy three suitable functional units are defined: 'battery packs with an identical mass', 'battery packs with an identical energy content' and 'battery packs with an identical one-charge range'.
The results show that the differences in the results between these three functional units are small and imply less variation on the results than the other uncertainties inherent to LCA studies. On the other hand, the results obtained using other, less adequate, functional units can be quite different.

Conclusions. When performing an LCA study, it's important to choose an appropriate functional unit. Most of the time, this choice is unambiguous. However, sometimes this choice is more complicated when different correlated parameters have to be considered, as it is the case for traction batteries. When using a realistic functional unit, the result is not influenced significantly by the choice of one out of the three suitable functional units.
Additionally, the life cycle assessment allowed concluding that three electric vehicle battery technologies have a comparable environmental impact: lead-acid, nickel-cadmium and nickel-metal hydride. Lithium-ion and sodium-nickel chloride have lower environmental impacts than the three previously cited technologies when used in a typical battery electric vehicle application.

Recommendations and Perspectives. The article describes the need to consider all relevant parameters for the choice of a functional unit for an electric vehicle battery, as this choice can influence the conclusions. A more standardised method to define the functional unit could avoid these differences and could make it possible to compare the results of different traction battery LCA studies more easily.

Keywords: Battery; electric vehicle; end-of-life-vehicle; environmental impact; functional unit; Life Cycle Assessment (LCA); sensitivity analysis

Introduction

In the framework of the European Subat-project, an environmental assessment of different battery technologies for electric and hybrid vehicles is carried out. The considered batteries are: lead-acid, nickel-cadmium, nickel-metal hydride, lithium-ion and sodium-nickel chloride. The LCA methodology was chosen to perform this analysis.

LCA studies the environmental aspects and potential impacts of a product throughout its life from raw material acquisition through production, use and disposal. It's its so-called 'cradle-to-grave' approach that makes LCA unique.

The three main stages considered in the LCA are the production phase, the use phase and the end-of-life phase.

LCA can be used as a decision support tool to compare the environmental impact of products. It is important to know that all stages of the LCA include some uncertainties. There are different classification systems available to distinguish these uncertainties; for example Huijbregts (1998) distinguished following categories: parameter uncertainty, model uncertainty, uncertainty due to choices, variability between objects/sources, special variability, temporal variability. Quite a lot of studies and articles have been published to calculate, to estimate and to minimize these uncertainties (e.g. Ciroth et al. 2004, Heijungs and Huijbregts 2004). To check the robustness of the results a sensitivity analysis has been performed.

The international standards of series ISO 14040 represent a widely accepted methodology (ISO 14040 1997). The ISO-14040 series distinguish four phases in LCA: the goal and scope definition (ISO 14041 1998), the inventory analysis (ISO 14041 1998), the life cycle impact assessment (LCIA) (ISO 14042 2000), and the interpretation (ISO 14043 2000). The definition of the goal and scope is one of the most critical parts of an LCA due to the strong influence on the result of the LCA (Klüppel 1998). A functional unit (FU) has to be defined in the scope phase. This FU is the central core of any life cycle assessment, since it provides the reference to which all other data in the assessment are compared (normalised). The impact of the adequate choice of a functional unit for the assessment of the environmental impact of a battery of an electric vehicle towards the global result will be discussed in this paper. Some detailed studies describe the impact of the choice of the functional unit in general on the result (e.g. Alsema 2000, Wigard 2001, Cooper 2003, Hischier and Reichart 2003).

As the result of the LCA will be used for decision support, it was important to choose an appropriate FU. Exhaustive and complete LCA studies about batteries are not widespread. (e.g. Rydh and Karlström 2002, Rydh 1999, Investire 2003). Specific LCA studies about traction batteries for electric vehicles are even rarer (Garcia and Schlüter 1996, Rantik 1999, Ishihara 1999, Biscaglia 2000, Van Autenboer 2004, Matheys 2004). In the few published LCA studies of batteries for battery electric vehicles (BEV), the chosen FU differs from one study to another. These differences can be explained because different parameters can influence the choice of one specific FU for a particular product. The impacts of these choices on the results are largely unknown and will be investigated in this article. An LCA is performed for the different appropriate FU as well as for some other known FU that are used in previously cited LCA studies. This allows to obtain an evaluation of the impact of the choice of FU on the global result.

1 Description of the Studied System

The definition of FU requires a thorough understanding of the analyzed system and an inventory of all the relevant parameters to be considered. The traction battery is the 'fuel tank' of the electric vehicle. The specific energy of the battery is one of the criteria determining the available quantity of energy. The chemical energy of this battery is transformed into electrical energy to drive the car. Once it is discharged, the battery can be charged by an external energy source. Amongst others, the specific energy, the energy efficiency, the number of cycles, are different from one battery technology to another. The energy efficiency is the ratio of the discharged energy (Wh) over the energy necessary to bring the battery back to its initial state of charge.

The way of using the BEV also determines the battery life. The used parameters for a technology are valid for one specific design of the battery. Differences occur with other battery designs or with different battery manufacturers.

An additional complication is that the energy consumption is dependent on the total mass of the car, which itself depends on the total mass of the battery.

2 Selection of the FU

For traction batteries there are different starting points to define an appropriate FU. An overview (and the definition) of several used FU in other LCA studies as well as a trivial FU (scenario 3) is given in **Table 1**.

Table 1: Examples of potential FU in literature

Scenario 1	Impact per km for an arbitrary chosen mass in function of range, including losses due to battery efficiency and energy consumption of the car (Garcia and Schluter 1999, Rantik 1999)
Scenario 2	Impact per kWh battery (Ishihara et al. 1999)
Scenario 3	Impact per kg battery
Scenario 4	Impact per km for a 'realistic' and arbitrary chosen mass in function of range, including losses due to battery efficiency and energy consumption of the car (Biscaglia and Coroller 2000)
Scenario 5	Impact for a certain energy content, including losses due to battery efficiency for the entire battery lifetime (Van Autenboer 2004, Matheys 2004)

The overview in Table 1 shows that different kinds of FU are used and that a more rational and coherent approach is needed. A summary of the different parameters that have to be considered when defining an FU (**Table 2**) shows that at least nine parameters have an influence on the definition of an FU. Some of these parameters are unrelated to the others, while some are intrinsically correlated to other parameters. For example an equal number of cycles, one-charge range and the depth of discharge (DOD) will imply an equal lifetime distance.

Table 2: Different parameters that determine the choice of an FU

Number of batteries (equal/different)
Depth of discharge (equal/different)
Lifetime distance (equal/different)
Additional consumption due battery mass (inclusive/exclusive)
Battery efficiency losses (inclusive/exclusive)
Energy content of battery pack (equal/different)
Mass of battery pack (equal/different)
One-charge range (equal/different)
Number of cycles (equal/different)

Table 3: Characteristics of the appropriate FU (=: these parameters are equal for all technologies; ≠: these parameters are (or can be) different for all the technologies)

	Battery mass	Energy content battery	Cycles/day	Life time range	Energy consumption (Wh/km)	Car range
FU Constant mass	=	≠	≠	=	=	≠
FU Constant energy content	≠	=	≠	=	≠	≠
FU Constant range	≠	≠	=	=	≠	=

The five first parameters of Table 2 cannot be chosen freely if wanting to obtain an appropriate reference basis. The reasons for this are firstly discussed.

Number of batteries: The number of possible charge/discharge cycles of a battery has to be taken into account in the calculations. The impact of a battery, with a lifetime that is twice the number of cycles of another battery having identical other parameters, is half the impact of the second one. So it is not advisable to compare a quantity of a given battery technology to the same quantity of another technology. The numbers of cycles have to be included in the definition of the FU.

Battery efficiency losses: Converting the chemical energy to electrical energy in the battery implies an energy loss and a consequent lower potential range of the vehicle. As the proportion of losses differs from one technology to another, these losses have to be included in the analysis.

Lifetime distance: When comparing battery technologies for an electric vehicle, it is crucial to compare the impact for an equal lifetime driven distance. Objectively, comparing different lifetime ranges for the different technologies is not acceptable.

Depth of discharge: An equal DOD and thus an equal percentage of available capacity is essential to compare the technologies. Another reason to include this parameter is that the total number of battery discharge cycles, required during the life of the vehicles, is strongly dependent on the DOD.

Additional consumption due to battery mass: As the mass of the battery and consequently the total mass of the car depends on the battery technology, a difference in energy consumption will be observed. This extra energy consumption has to be included in the LCA calculations, as it influences the overall impact due the emissions related to electricity production.

As a summary, five parameters cannot be chosen freely and have to be considered in each functional unit: an equal depth of discharge should be assumed, the number of batteries required during the life of the vehicle should be calculated, the energy losses in the battery and the additional vehicle consumption due to the battery mass have to be included and the same lifetime distance has to be covered.

Out of the other parameters of Table 2 (mass of the battery, energy of the battery, one-charge range of the battery, number of cycles during lifetime), one of the first three has to be considered as a constant in order to have an FU with some practical significance. Each of these possibilities results in a conceptually different FU. The last parameter (number of cycles during lifetime) will be dependent on the choice of the other parameters (lifetime range, energy content etc.).

The differences between these three scenarios (FU constant mass, FU constant energy content and FU constant range) are summarized in **Table 3**. Table 3 clearly illustrates the similarity (=) and difference (≠) of the different parameters for the different scenarios (FU) for the different technologies.

Based on all these parameters and technical data, the required number of batteries for the different technologies can be calculated. Although in practice an integer number of batteries will be needed, these numbers of batteries will not be rounded to an integer number, because this rounding can change the total result significantly. For example, if theoretically 1.01 battery is needed, rounding-up to 2 batteries (required in practice) will introduce major variations of the global results. This assumption would result in an impact that is almost twice as high.

3 Advantages and Disadvantages of the Selected FU

As shown in **Table 4**, each of the three appropriate FU has advantages and disadvantages. The importance allocated to

Table 4: Advantages and disadvantages of the different FU with constant life time range of the car

FU Constant mass	Advantages	• The energy consumption of the vehicles is the same for the different battery technologies • The most appropriate battery mass can be selected as a function of the size and the energy consumption of the vehicle
	Disadvantages	• Due to the different specific energies of the batteries, the ranges differ from one technology to another • The energy contents of the batteries differ from one technology to another • The number of cycles required to cover the total distance differs from one technology to another
FU Constant energy content	Advantages	• The same global energy content
	Disadvantages	• Ranges differ from one technology to another • Energy consumption differs from one technology to another (different mass) • The number of cycles required to cover the total distance differs from one technology to another
FU Constant range	Advantages	• The vehicle is able to cover the same distance independently of the technology. As a consequence, the same number of cycles is needed to cover the lifetime distance of the vehicle
	Disadvantages	• The masses and energy contents differ from one battery technology to another • The assumptions are conceptually more complicated, compared to the other FU • The same payload is delivered

these advantages and disadvantages by the investigator will obviously be determinant when having to decide which FU to choose. An LCA will be performed for these three FU to illustrate the impact of the choice on the global result.

4 LCA Assumptions: Model, Used Data and Assumptions

The software used to perform the analysis is SimaPro 6.0, while Eco-indicator 99 (hierarchist version) is chosen as impact assessment method, for it's a quite standard and widespread methodology (VROM 1999). The results are given in Eco-indicator points. An Eco-indicator point (Pt) is equivalent to one thousandth of the yearly environmental burden of one average European inhabitant.

Our model is based on a small car like the electric Peugeot 106. The net weight of the car, excluding the battery, including the driver's weight (75 kg), is 888 kg. A DOD of the battery of 80% is choosen (deep cycling). The self-discharge of the batteries and the maintenance were not considered for any of the technologies. The additional energy consumption due to the battery mass is simulated with the help of the Vehicle Simulation Programme, VSP (Van Mierlo and Maggetto 2004). The ECE cycle is taken as the reference cycle (Van den Bossche 2003). The electricity mix of the European Union (EU-25) for the year 2003 is used.

The LCA is performed for the most widespread battery technologies. The inventory analysis is based on information obtained by intensively interrogating the worldwide industry, on information available in the literature and information obtained through commercially available databases.

The main used technical characteristics for the different battery technologies are listed in **Table 5**.

As the sodium-nickel chloride battery needs to be heated when it is not used, an extra energy loss of 7.2% is taken into account.

Table 5: Used characteristics of the different battery technologies

	Specific Energy (Wh/kg)	Number of cycles	Energy efficiency
Pb-acid	40	500	0.825
NiCd	60	1350	0.725
NiMH	70	1350	0.7
Li-ion	125	1000	0.9
Zebra	125	1000	0.925

Depending on the FU, a mass of 300 kg, an energy content of the battery pack of 12 kWh or a one-charge range of 60 km is chosen. In all these scenarios the lifetime distance is set to 160000 km. All these assumptions are realistic for this kind of car.

A sensitivity analysis is performed to assess the effects of the assumptions (concerning average battery composition, energy consumption…) and of possible variations in the collected battery percentage on the results. More details concerning the sensitivity analysis can be found in SUBAT's final report (2005).

5 Results and Discussion

Based on the previously mentioned assumptions, three FU were selected: batteries with constant mass, constant energy or constant one-charge driving range. The total environmental impact (in Eco-Indicator 99 points) for these three FU is shown in **Fig. 1** for the different technologies. The results are subdivided in the contribution of each of the different stages of the life cycle of the battery (assembly + recycling, energy losses due to the battery mass and energy losses due to energy efficiency of the battery).

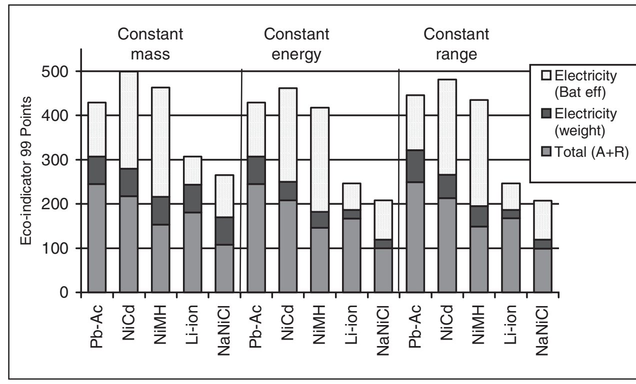

Fig. 1: Results of the LCA for the different FU and battery technologies

Fig. 1 clearly illustrates that the obtained impact for these selected FU are quite similar. The order of magnitude of the impact of the different battery technologies remains the same. The total impact slightly differs from one scenario to another, but the differences between the different scenarios (5–10%) are smaller than other inherent uncertainties of LCA studies.

Globally, with regard to the different FU, the total impact in the FU 'constant mass' is the highest. This is due to the higher battery masses carried by the car compared to the other FU's and the corresponding higher electricity consumptions. The results of the scenario 'constant energy' and 'constant one-charge range' are very similar as the corresponding masses for these FU are quite similar.

A sensitivity analysis of the model parameters has been performed for the FU 'constant range' (**Fig. 2**). The values are normalized (Pb-acid = 100). Fig.2 demonstrates that the

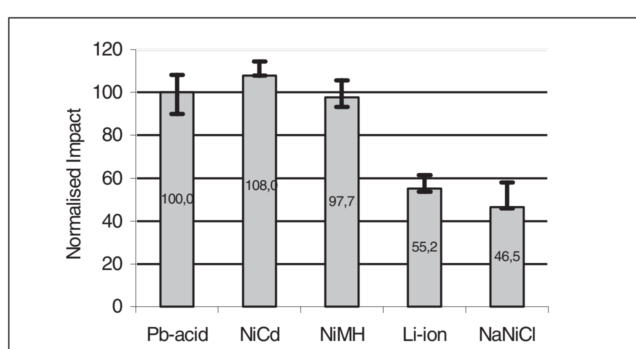

Fig. 2: Results of sensitivity analysis of FU constant range

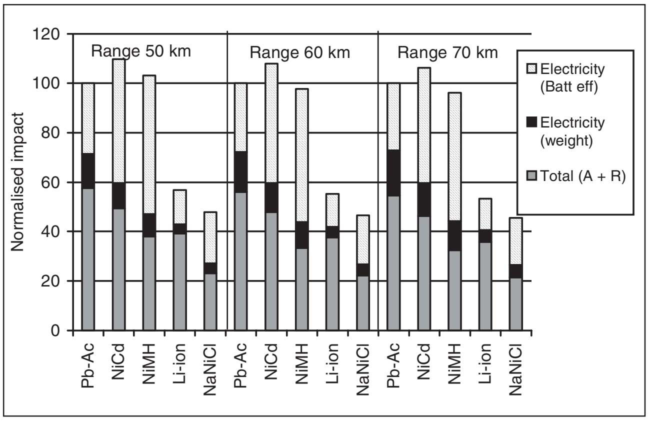

Fig. 3: Normalised environmental impact when the 'one-charge range' is modified to 50 or 70 km

mentioned assumptions did not have any significant impact on the results in the sense that the conclusions remain the same and that the results are reliable.

The impact of the choice of another constant range as an FU was also investigated. These analyses show (**Fig. 3**) that for a range increased or decreased by 20%, the normalised values (Pb-acid = 100) do not differ by more than 5% from the values of the standard range. For the other FU ('constant mass' and 'constant energy'), comparable deviations in the sensitivity analysis are obtained.

Keeping the results of the sensitivity analysis in mind, the life cycle assessment allowed concluding that three electric vehicle battery technologies have a comparable environmental impact: lead-acid, nickel-cadmium and nickel-metal hydride. When used in a typical battery electric vehicle application, lithium-ion and sodium-nickel chloride have lower environmental impacts than the three previously mentioned technologies.

On the contrary, other results are obtained when using other FU than the three selected FU. The variation can be much higher and the environmental ranking of the different technologies may change. As an example, the results of the LCA studies for scenarios 1 to 3 (see Table 1) and the reference scenario 'constant range' are shown in **Fig. 4**. These scenarios were based on existing FU in the literature (Garcia and Schlüter 1999, Rantik 1999, Ishihara et al. 1999). To enable the comparison of these scenarios, the values are normalised to Pb-acid = 100 in all scenarios.

Fig. 4 illustrates that the results for the four other FU suggested in the literature are quite different and illustrates the impact of the choice of the FU on the results, emphasizing the importance of the choice of an appropriate FU. These differences due to the choice of a particular FU depend on the inclusion of different parameters in the different FU. Depending on these choices the score will be different and the environmental ranking can vary. The advantage of the three selected FU ('constant mass', 'constant range' and 'constant energy content') compared to others is that these FU reflect the real-world system very realistically.

6 Conclusions

The ISO-14041 standards only note that the selection of a functional unit must be clearly defined and that the FU must be measurable (ISO 14041, 1998). This is a rather unclear specification especially when wanting to use LCA for the comparison of products when different potential functional units exist and when all of these different FU are in accordance with the ISO standards.

The influence of the choice of one of these FU on the results is particularly important when the results of the LCA are meant to be used as a decision support tool. This article illustrates that the results of an LCA are strongly depending on the chosen FU and that this choice introduces a kind of uncertainty. Therefore, it is important to choose the most appropriate and widely accepted FU in relation to the application. The functional unit should be selected corresponding to real life use of an electric vehicle, as this was the considered application. For other battery applications, e.g. cellular phones, other functional units should be selected.

Most of the time, the choice is unambiguous. However, especially when different correlated parameters have to be

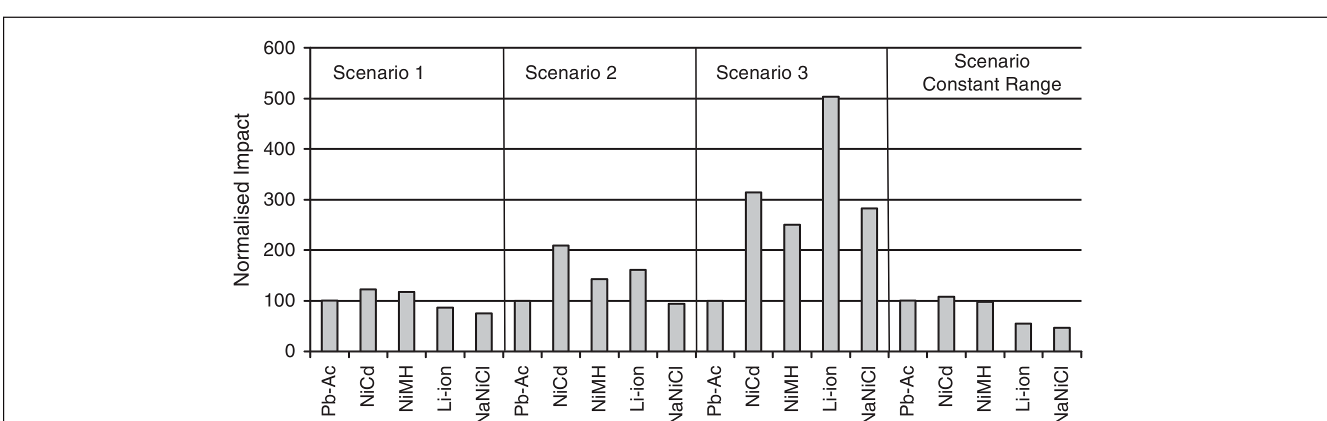

Fig. 4: Results of the other FU available in the literature (results are normalized to Pb-acid=100)

considered, as it is the case for traction batteries, this choice gets more complicated. The results of the different suitable functional units are nearly similar and as a consequence, the result is not markedly influenced by the choice of the FU when choosing one of the three suitable functional units. The results can be quite different for other FU (than these three), as another choice is most of the time a simplification of the real system.

Additionally, the life cycle assessment allowed concluding that three electric vehicle battery technologies have a comparable environmental impact: lead-acid, nickel-cadmium and nickel-metal hydride. Lithium-ion and sodium-nickel chloride have lower environmental impacts than the three previously mentioned technologies when used in a typical battery electric vehicle application.

7 Recommendations and Perspectives

The article describes the need to consider all relevant parameters for the choice of a functional unit for an electric vehicle battery, as this choice can influence the results and the conclusion. A more standardised method to define the functional unit could avoid these differences and could make it possible to compare the results of different LCA studies more easily.

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References

Alsema EA (2000): Environmental life cycle assessment of solar home systems. Department of Science Technology and Society, Utrecht University, Utrecht, The Netherlands, pp 89

Biscaglia S, Coroller P (2000): Life Cycle Analysis of Electric Vehicle. Proceedings Electric Vehicle Symposium 17, Montreal, Canada, pp 17

Ciroth A, Fleischer G, Steinbach J (2004): Uncertainty Calculation in Life Cycle Assessments: A combined model of simulation and approximation. Int J LCA 9, 216–226

Cooper JS (2003): Specifying Functional Units and Reference Flows for Comparable Alternatives. Int J LCA 8, 337–349

Garcia MJA, Schlüter F (1996): Life-cycle assessment for batteries of Electric Vehicles. Master thesis, School of Technology Management and economics, Department of Transportation and Logistics, Chalmers University of Technology, Götenborg, pp 267

Heijungs R, Huijbregts MAJ (2004): A Review of Approaches to Treat Uncertainty in LCA. Proceedings iEMSs 2004, Osnabrück, Germany, pp 8

Hischier R, Reichart I (2003): Multifunctional Electronic Media - Traditional Media. The Problem of an Adequate Functional Unit: A case study of a printed newspaper, an internet newspaper and a TV broadcast. Int J LCA 8, 201–208

Huijbregts MAJ (1998): Application of Uncertainty and Variability in LCA. Part I: A General Framework for the Analysis of Uncertainty and Variability in Life Cycle Assessment. Int J LCA 3, 273–280

Investire (Investigation on Storage Technologies for Intermittent Renewable Energies) (2003): European Project.WP5 Environmental Issues, pp 25

Ishihara K, Nishimura K, Uchiyama Y (1999): Lifecycle Analysis of Electric Vehicles with Advanced Batteries in Japan. Proceedings Electric Vehicle Symposium 16, Beijing, China, pp 7

ISO 14040 (1997): Environmental management – Life cycle assessment – Principles and framework. International Standard ISO 14040. Geneva, Switzerland

ISO 14041 (1998): Environmental management – Life cycle assessment – Life cycle assessment – Goal and scope definition and inventory analysis. International Standard ISO 14041. Geneva, Switzerland

ISO 14042 (2000): Environmental management – Life cycle assessment – Life cycle impact assessment. International Standard ISO 14042. Geneva, Switzerland

ISO 14043 (2000): Environmental management – Life cycle assessment – Life cycle interpretation. International Standard ISO 14042. Geneva, Switzerland

Klüppel H-J (1998): ISO 14041: Environmental management –Life Cycle Assessment – Goal and Scope Definition – Inventory Analysis. Int J LCA 3, 301

Matheys J (2004): Life Cycle Assessment of NiCd traction batteries. Master thesis. Department of Electrotechnical Engineering and Energy Technology. Vrije Universiteit Brussel, Belgium

Official Journal of the European Communities (2000): End-of-life Vehicle Directive 2000/53/EC. Available online <http://europa.eu.int/eur-lex/pri/en/oj/dat/2000/l_269/l_26920001021en00340042.pdf>

Rantik M (1999): Life Cycle Assessment of Five Batteries for Electric Vehicles under Different Charging Regimes. KFB-Meddelande, pp 28

Rydh CJ (1999): Environmental assessment of vanadium redox and lead-acid batteries for stationary energy storage. J Power Sources 80, 21–29

Rydh C J, Karlström M (2002): Life cycle inventory of recycling portable nickel–cadmium batteries. Resour, Conserv Recycling 34, 289–309

SUBAT (2005): Final public report. Available online <www.battery-electric.com>, pp 60

Van Autenboer W (2004): Life Cycle Assessment of Lead-acid traction batteries. Department of Electrotechnical Engineering and Energy Technology. Master thesis. Vrije Universiteit Brussel, Belgium, pp 63

Van den Bossche P (2003): The electric vehicle: Raising the standards. PhD thesis Vrije Universiteit Brussel, Brussels, pp 485

Van Mierlo J, Maggetto G (2004): Innovative Iteration Algorithm for a Vehicle Simulation Program. IEEE Trans Veh Technol 53, 401–412

VROM (Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer) (1999): The Ecoindicator 99: A damage oriented method for Life Cycle Impact Assessment. Methodology Report, Publicatiereeks productenbeleid, nr. 1999/36A. The Netherlands, pp 144

Wiegard J (2001): Quantification of Greenhouse Gases at Visy Industries using Life Cycle Assessment. Master Thesis. Swinburne University of Technology, Australia, pp 165

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